Uncertainties in electron density profiles retrieved by COSMIC GPS radio occultations

P. Alexander\textsuperscript{1}, A. de la Torre\textsuperscript{2}, P. Llamedo\textsuperscript{2}, R. Hierro\textsuperscript{2} and N. Yen\textsuperscript{3}

\textsuperscript{1}Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, 1428 Buenos Aires, Argentina
\textsuperscript{2}Facultad de Ingeniería, Universidad Austral, Buenos Aires, Argentina
\textsuperscript{3}National Space Organization, Taiwan
Introduction

- Immediately after launch the six COSMIC satellites orbited in very close proximity for a few months, so during this period the data was particularly clustered in geographical areas and time.
- This offered an excellent opportunity to evaluate the precision of the retrieved profiles through the use of nearly collocated and simultaneous observations.
- The idea is not new. It has been mainly used in the neutral atmosphere. In the ionosphere it has been applied to earlier product versions, which later were improved or corrected.
- This study uses the most newly post-processed data (version 2010.2640) provided by CDAAC (COSMIC Data Analysis and Archive Center). We statistically evaluated the precision of GPS radio occultations (RO) in the ionosphere by using the level 2 electron density product.
Uncertainties

- Precision ("repeatability") may be assessed by repeating observations, but usually measurements cannot be repeated under exactly the same conditions. Here we set requirements to keep small the separations in time and space of pairs.

- GPS RO observations are not point measurements, but long line integrals. However, they are treated as point values located in the tangent point to the Earth of the ray between both satellites. Different but simultaneous observations at the same tangent point could be sampling different atmospheric zones. Therefore, significant differences in ionospheric properties assigned to a given point and time from diverse RO measurements may appear. This "representativeness error" can be minimized here by the nearly collocated and simultaneous RO.
• In fact, the main cause of error in the GPS RO electron density profile retrievals is attributed to the horizontal inhomogeneity affecting the assumption of spherical symmetry.
• Accuracy ("exactitude") cannot be analyzed in detail here, as we have no simultaneously collocated global and reliable reference measurements from other platforms available.
• The ionospheric outcome may have poor accuracy, but the precision could exhibit better values.
Data processing

• We considered days 194-208 (July) of year 2006 available at CDAAC, processing almost 30,000 RO. It has recently been reported that data before day 194 are not high quality due to receiver tracking issues, so it is strongly recommended to focus the efforts after that day (cdaac-www.cosmic.ucar.edu/cdaac/products.html#cosmic). We used 15 days to avoid any seasonal variation of data.

• There is a delicate compromise between narrowing the acceptable separation standard in space and time of both RO of every pair (to ensure that we are measuring the "same" observable) and keeping a large number of cases to be able to perform satisfactory statistics. We chose a time and horizontal separation of less than 1 min and less than 10 km between both soundings. Some previous ionospheric work performed evaluations with stricter constraints, but used data from the later considered dubious period. All the pairs that we detected belong to satellites 3 and 4. We did not exclude cases with unphysical negative electron density values.
Our study separated the data according to day or night and to 5 latitudinal zones, so that each group possessed some degree of homogeneity, which we also evaluated.

<table>
<thead>
<tr>
<th>Zone of Latitude</th>
<th>Day</th>
<th>Night</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>55° to 90°</td>
<td>84</td>
<td>3</td>
<td>87</td>
</tr>
<tr>
<td>20° to 55°</td>
<td>265</td>
<td>136</td>
<td>401</td>
</tr>
<tr>
<td>−20° to 20°</td>
<td>129</td>
<td>109</td>
<td>238</td>
</tr>
<tr>
<td>−55° to −20°</td>
<td>171</td>
<td>287</td>
<td>458</td>
</tr>
<tr>
<td>−90° to −55°</td>
<td>4</td>
<td>65</td>
<td>69</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>653</td>
<td>600</td>
<td>1253</td>
</tr>
</tbody>
</table>

- During July there is a prevalence of day and night pairs respectively in the Northern and the Southern Hemispheres. In particular, almost all cases at high latitudes occur during the night and day respectively in the southern and northern halves.
- Due to the configuration of the constellation most pairs are found at middle latitudes and much less close to the poles.
- There is a slightly better coverage of the southern half in our sample (we do not know if there is an explanation for this).
Number of RO retrievals per day for satellite 4 (as a proxy for the potential number of nearly collocated and simultaneous cases) and the number of pairs in fact found. A decreasing trend of both amounts may be seen. Any additional day added to the 15 ones used will contribute in average with less cases (and in addition it will decrease the homogeneity degree of data).
• We first calculated the average electron density profile against altitude for each of the 10 groups.
• In order to check the homogeneous degree of each group we also computed the standard deviation of the profiles against altitude.
• We assessed precision against height by the root-mean-square (RMS) difference of vertical electron density profiles between all the pairs in each group.
The available data provide information on the lines of sight (LOS) of each RO and if it is a setting or rising event:

- We analyzed 26 pairs which exhibited a valuable property to test the assumption of spherical symmetry in the electron density retrievals: both RO of the pair had significantly different lines of sight angles (more than 10°).
- We compared the RMS against height for setting and rising pairs in group DMN (265 cases) in order to see if they produce a significantly different outcome.

a = 10-20°
b = 20-40°
a = setting
b = rising
Conclusions

• The best precision results in this work are found around the electron density F peak (about 1%) and they slightly degrade upwards.

• In all day groups precision is better than 10% above 120 km altitude.

• For the night cases precision generally improves over 10 % above about 200 km height, and from there upwards the best performance is found in the Northern Hemisphere.

• Up to 100-200 km (depending on each group), the uncertainty associated to the precision is on the order of the measured electron density values, or there is even a worse outcome, the retrieved values may be negative. We must conclude that we cannot be very much confident about the electron density values at these altitudes in general. Is the lack of precision somehow related to the lack of homogeneity of each group ?

• Large RMS around 100 km altitude was already noticed by Schreiner et al. (2007) and was likely considered a possible combination of effects: the inability of GPS RO of a good sampling of sharp vertical structures, the effect of horizontal variations due to sporadic events in the E-layer, signal defocusing, natural spatial variations and in lesser extent thermal noise.
• From all the pairs analyzed, there were just 26 that exhibited a difference between LOS angles of both RO larger than 10°. From their analysis, we find no clear representativeness error introduced by the spherical assumption above 120 km height. However, the statistical power of the results is low.

• Setting RO show a significantly better precision than rising ones (firmware for rising occultations was tested and modified frequently during this period as mentioned by Schreiner et al. 2007).

• Our calculations reproduce previous results on a lower reliability of the retrieved electron density at low altitudes (Yue et al. 2010) and on the fact that day groups show in general a better precision performance than night ones (Wu et al. 2009).